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Pratt & Whitney – FAA CLEEN II Consortium
October 28, 2020

Pratt & Whitney's CLEEN II Technologies

Today's Agenda

- Overview of RTX and Pratt & Whitney
- Summary of P&W's CLEEN II Efforts
- Overview of P&W's CLEEN II Compressor Technologies
- Overview of P&W's CLEEN II Turbine Technologies
- Overall mission performance and fleet impacts (initial estimates)
- Geared Turbofan™ entry into service and applicability of CLEEN II technology to future products

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Our company

Raytheon Technologies

195,000

employees worldwide

190+

years of combined innovation and leadership

$74* billion

2019 sales

$8 billion

annual customer- and company-funded R&D spend

10

enterprisewide development capability centers

* TOTAL COMPANY REVENUES FOR RAYTHEON TECHNOLOGIES EXCLUDES INTERCOMPANY SALES BETWEEN THE BUSINESSES.

Raytheon Technologies

Our businesses

Collins Aerospace

$26B 2019 sales

78,000 employees

186 customer countries

Pratt & Whitney

$21B 2019 sales

43,000 employees

195 customer countries

Raytheon Intelligence & Space

$15B 2019 sales

39,000 employees

40 customer countries

Raytheon Missiles & Defense

$16B 2019 sales

30,000 employees

50 customer countries

Raytheon Technologies

Legacy

Boeing 757

Airbus A320

Boeing 767

Airbus A330

Boeing 777

Airbus A380

GTF

Airbus A320neo

Mitsubishi MRJ

Airbus A220

Embraer 190/195-E2

Irkut MC-21

Embraer 175-E2

P&W Powers Commercial Legacy Fleets and the Exclusive Geared Turbofan Fleets

GTF ENGINE FAMILY

FOR LARGE COMMERCIAL AIRCRAFT

AND REGIONAL JETS

17,000 – 33,000
Pounds Thrust Class

16% Improvement in fuel efficiency

50% Reduction in regulated NOx emissions

75% Reduction in noise footprint

GTF Technology Provides Major Benefits

Pratt & Whitney ADVANCED Manufacturing

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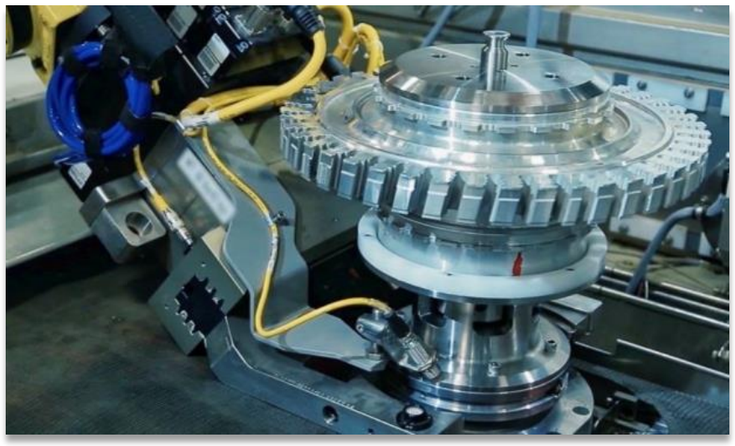

Investment in facilities for productivity

Investment in automated manufacturing

Investment in inspection technology for quality

State of the Art Technology to Produce Advanced Aerospace Products

Sustainability goals at Pratt & Whitney

GO BEYOND

Strive to be the best aerospace engine company FOR the world

FOR OUR PRODUCTS

Emissions
Reduce the environmental impacts of our products
Work with our customers to reduce in-service impacts

Sustainable Products
Design, manufacture and service products to minimize impacts
Use Ecodesign to drive product innovation

FOR OUR SITES

Zero Waste
All by-products 100% recycled
Increase efficiency and reduce “non-product” output

Carbon Neutral
Use only sustainable energy sources
Lower our footprint to avoid future impacts and costs

FOR OUR PEOPLE

Influence
Be a force for positive change
Support and engage employees and communities in building a better future

Owning Our Future

Pratt & Whitney's CLEEN II Technologies

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Pratt & Whitney's CLEEN II Technologies

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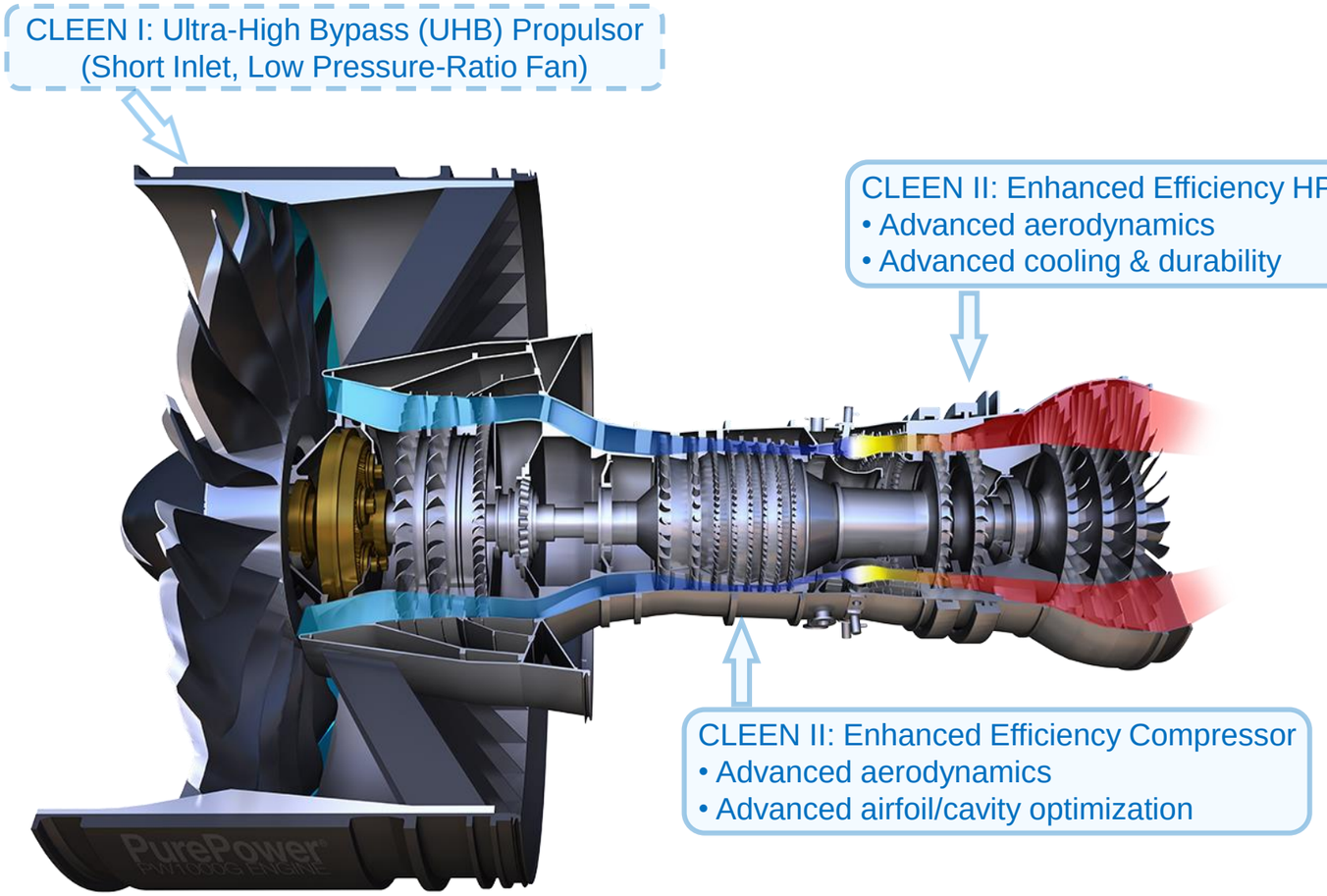
Improved propulsive efficiency enabled by Geared Turbofan™ architecture

CLEEN II builds upon CLEEN I for overall GTF engine architecture efficiency benefits

CLEEN II compressor and turbine technologies together improve the thermodynamic efficiency of the GTF architecture.

Pratt and Whitney is rapidly introducing CLEEN technologies to the GTF fleet

Leads to a 1.6-2.0% total fuel burn reduction



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CLEEN II Progress To-Date

HPC rig scope completed in 2017

Engine demonstration program for HPC Technologies completed

HPT Cascade testing completed

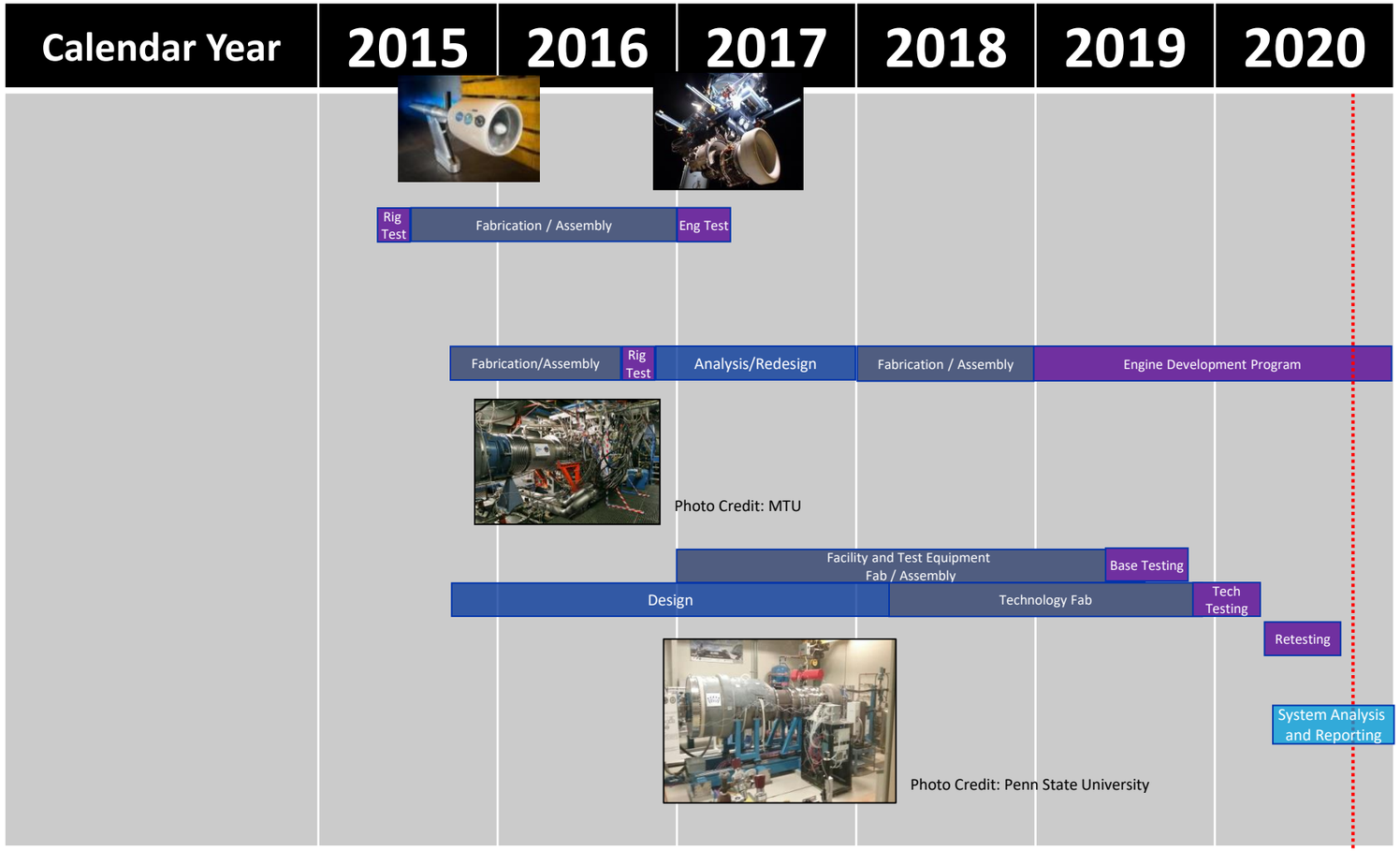
PSU HPT START facility upgrade completed

Technology hardware fabrication complete

HPT testing complete

HPT START data processing complete

System level assessment in-work



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Compressor Aero Efficiency Technologies

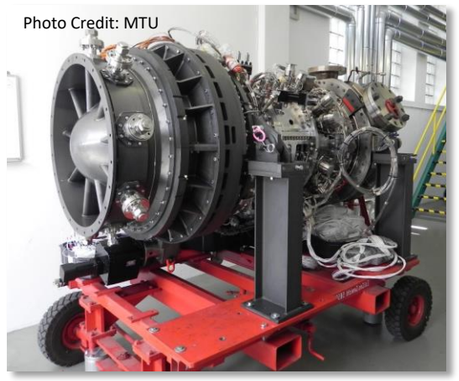
Benefits:

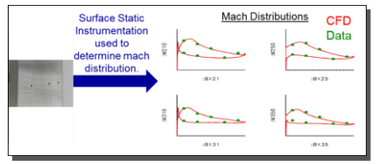
Improved thermal efficiency

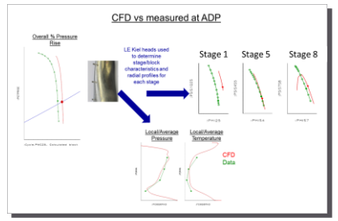
- ~ 0.8 – 1.0% fuel burn reduction

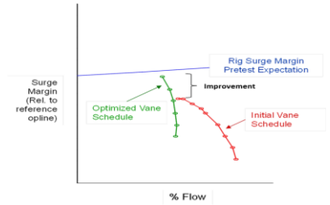
Risks/Mitigations

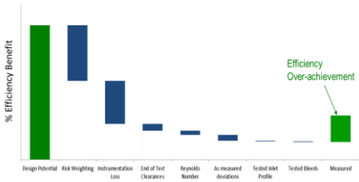
- No risks identified at this time











2016-17 Rig Test → Data Reduction → Module Benefits

Objectives:

Demonstrate improved high pressure compressor efficiency via advanced aerodynamic airfoil optimization

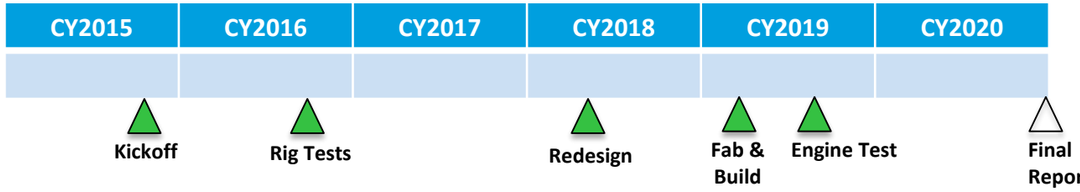
Work Statement:

Continue the TRL advancement of compressor aero-efficiency technologies via detailed design, fabrication, full-scale rig tests, and engine validation.

Prior Accomplishments:

- Redesign completed, component fabrication complete, testing complete

Schedule & Planned Milestones:



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HPC Technology Rig Complete

CLEEN II compressor aero design has successfully completed ground and flight test, bringing HPC technology to TRL 7

Tools developed and knowledge gained on aero performance will be introduced into GTF product line

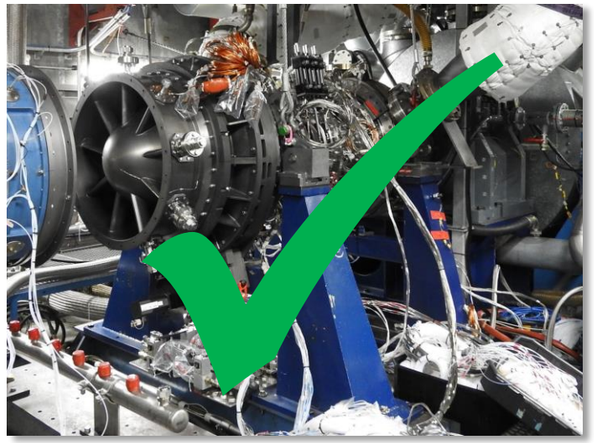

Photo Credit: MTU

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Turbine Aero Efficiency and Durability Technologies

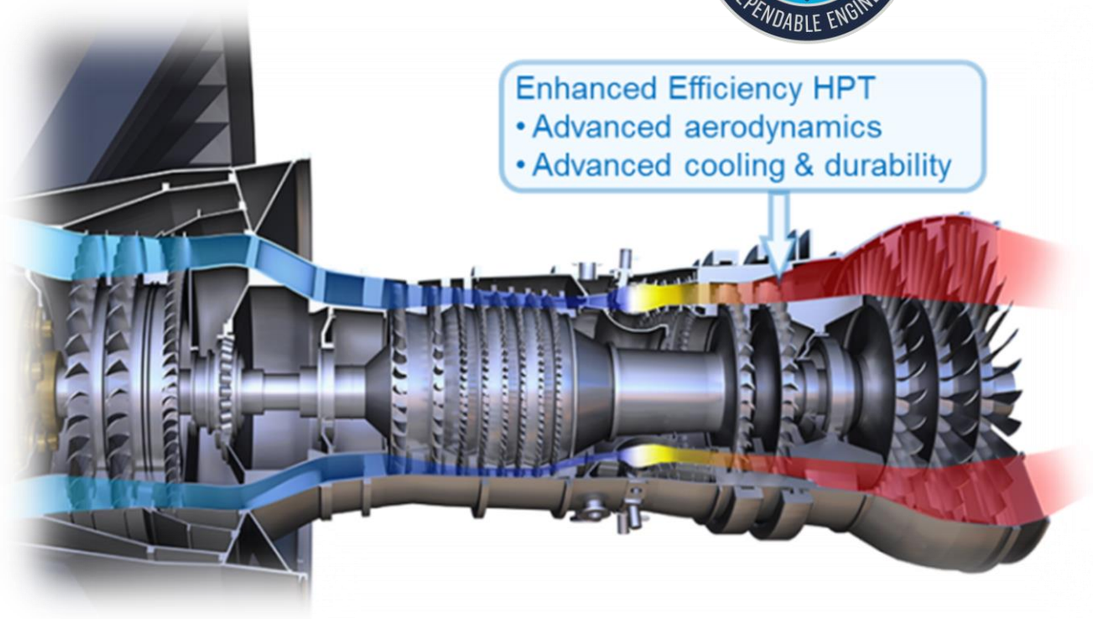
Benefits:

Improved thermal efficiency

- ~ 0.8 – 1.0% fuel burn reduction

Risks/Mitigations

None identified at this time



Objectives: *Demonstrate improved high pressure turbine efficiency via advanced aerodynamic airfoil and durability optimization*

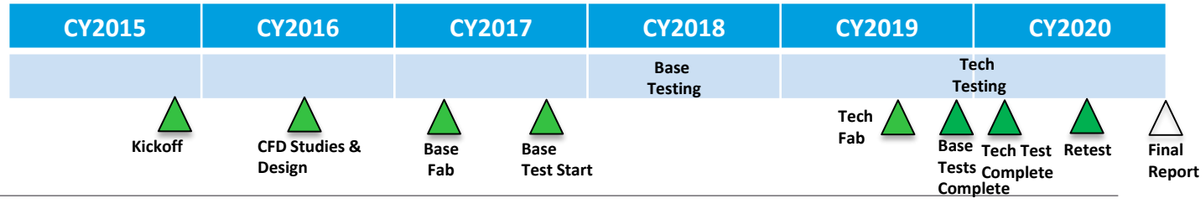
Work Statement:

Continue the TRL advancement of turbine aero-efficiency and durability technologies via CFD studies, detailed design, fabrication, and full-scale rig tests.

Prior Accomplishments:

- Completed Baseline Blade Aero testing
- Completed Baseline & Technology Blade IR Durability testing
- Completed Technology Blade Aero testing
- Completed Baseline & Technology Blade Retest

Schedule & Planned Milestones:



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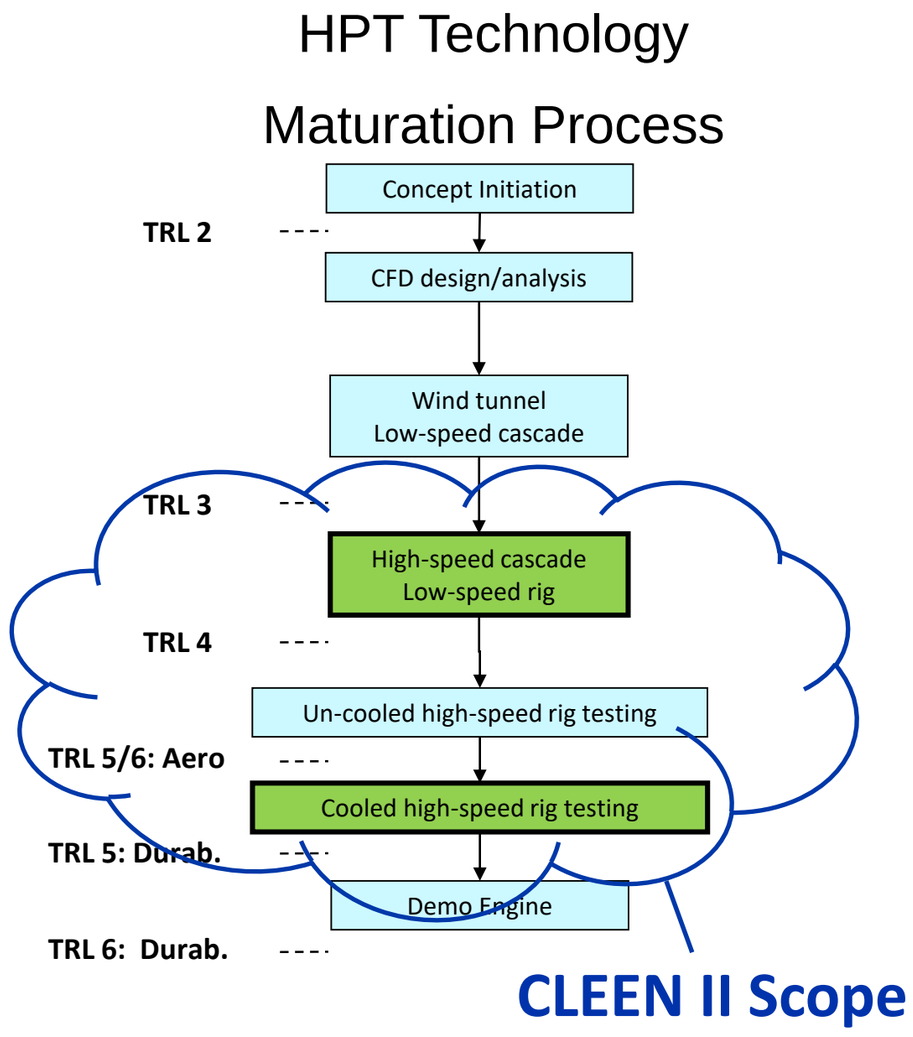
HPT Technology Maturation Strategy

Previous investment from P&W has brought HPT technologies through Technology Readiness Level (TRL) 3

- CFD design and analysis for conceptual design of the technologies
- Low speed wind tunnel testing for initial learning

Under FAA funding, bringing HPT technologies to TRL 5 for durability and TRL6 for aero technologies



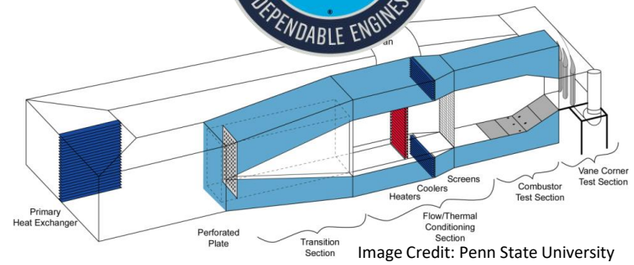


Image Credit: Penn State University

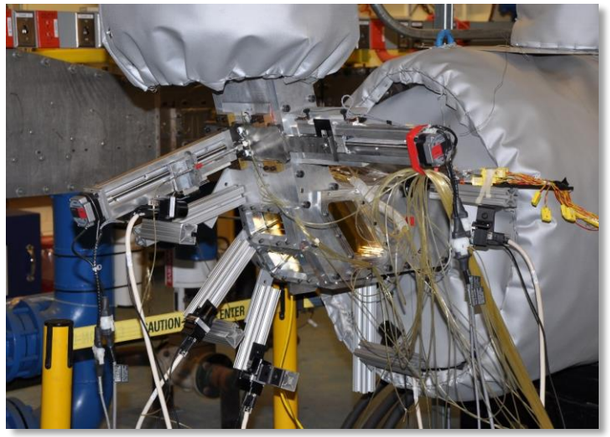


Image Credit: Penn State University

Image Credit: Penn State University

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HPT Technology Status - Schedule

Conceptual design work started prior to CLEEN II contract start, FAA has helped mature the HPT technologies beyond TRL 3

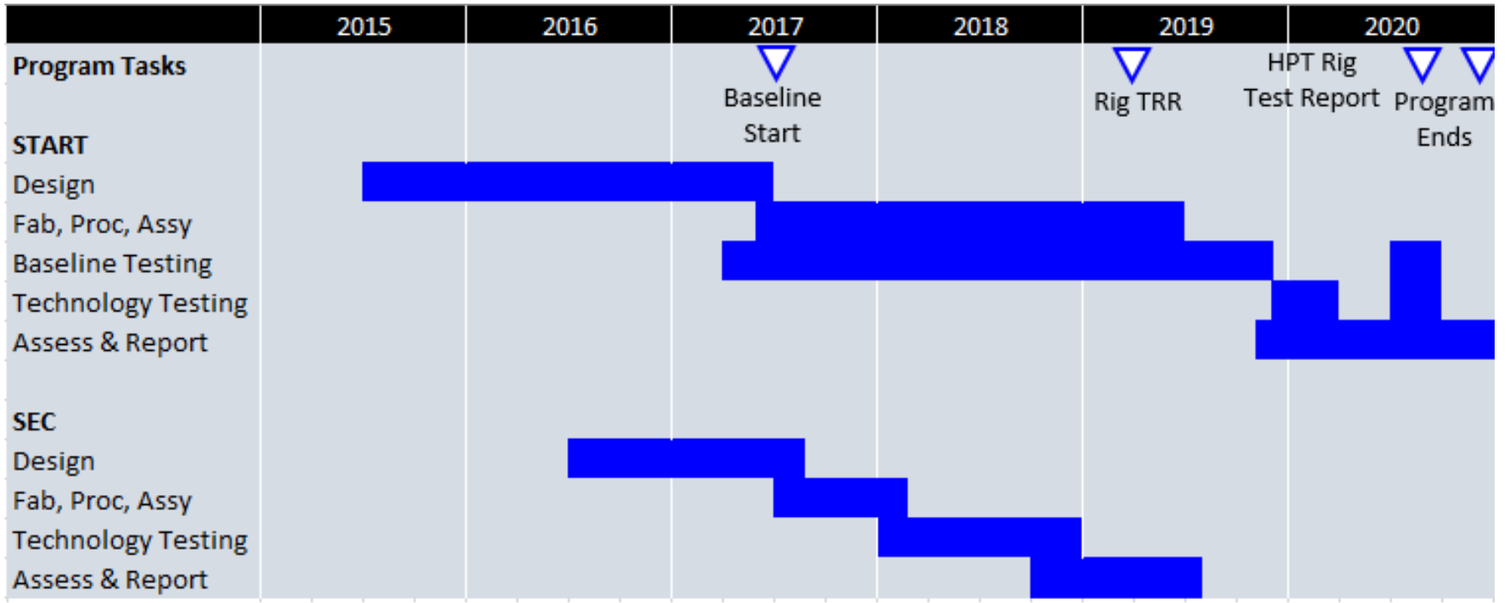
Single Element Cascade testing completed

Baseline Blade START testing completed Dec. 2019

Technology Blade START testing completed Mar. 2020

COVID shutdown and instrumentation issues resulted in extended program completion date

Baseline and Technology Blade repeat aero testing completed September 2020



Pratt & Whitney's CLEEN II Technologies

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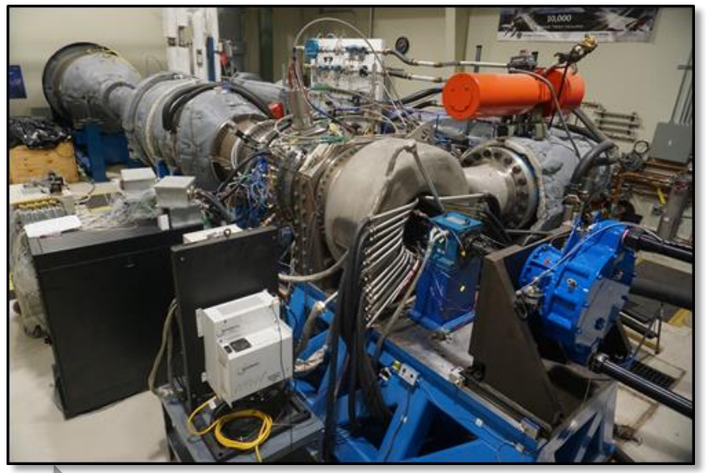
Penn State START Facility – Background

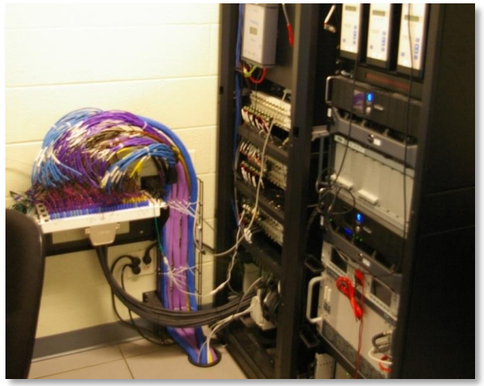
START = Steady Thermal Aero Research Turbine.

Test section is modeled after Pratt & Whitney's GTF high pressure turbine module

~$10M combined investment into the facility over the past 5 years

Pratt & Whitney Center of Excellence, World Class Facility





2013 → **2020**

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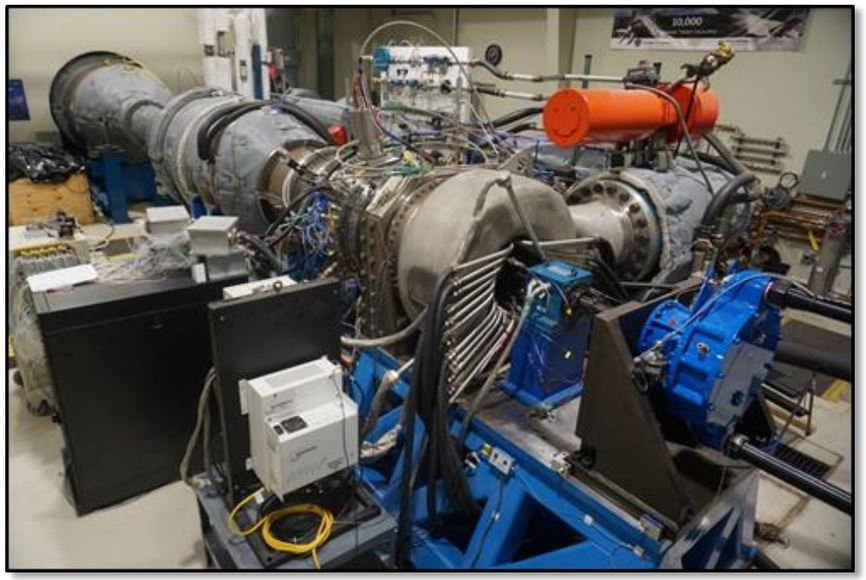
Penn State START Facility – Objectives

Validate predictions for novel aero/thermal component designs in order to correlate analytical tools for CLEEN II technologies

Compare baseline and advanced aero/thermal technologies at representative operating conditions

Build upon completed SEC testing; verifies full-span 3-dimensional aero



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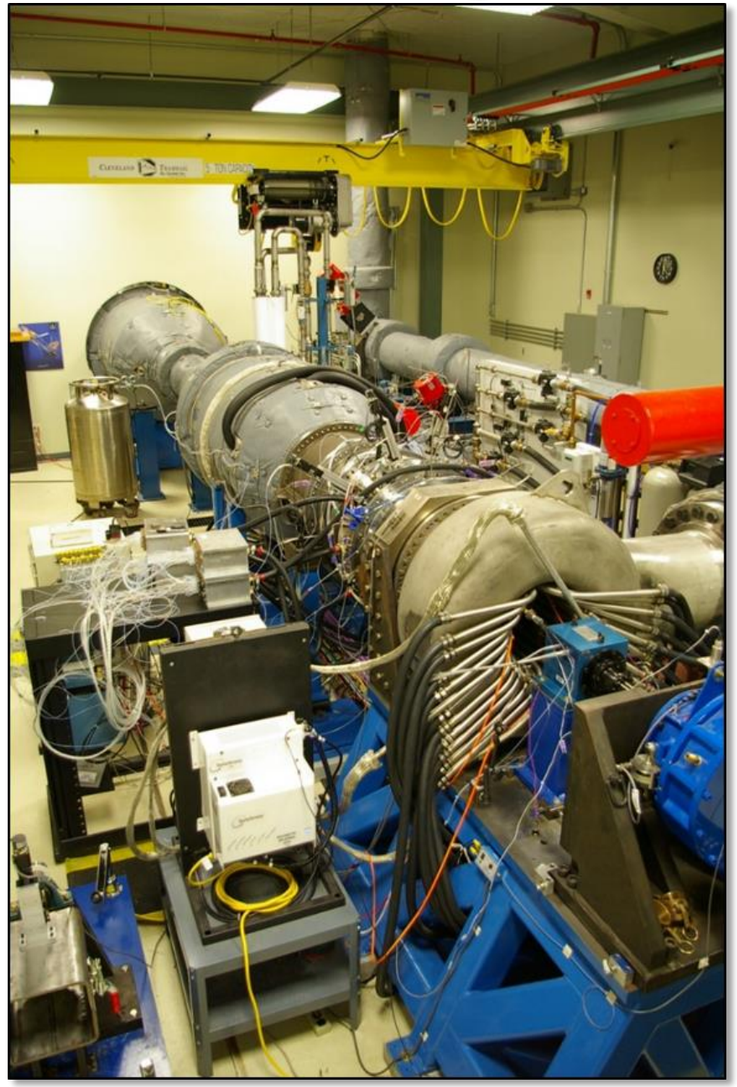
Penn State START Facility – Execution

- ✓ Procurement and assembly of "Phase II" START rig facility completed
- ✓ START facility shakedown completed
- ✓ Cavity Aero testing completed
- ✓ Analytical aero/thermal pre-test predictions completed
- ✓ Aero testing of baseline GTF technology completed
- ✓ CLEEN II advanced technology blade aero/thermal instrumentation fabrication completed
- ✓ CLEEN II advanced technology blade fabrication completed
- ✓ All rig hardware for CLEEN II technology blade delivered
- ✓ Thermal testing of baseline & advanced technology blades completed
- ✓ Aero testing of advanced technology blades completed



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Penn State START Facility – Aero Pretest Predictions

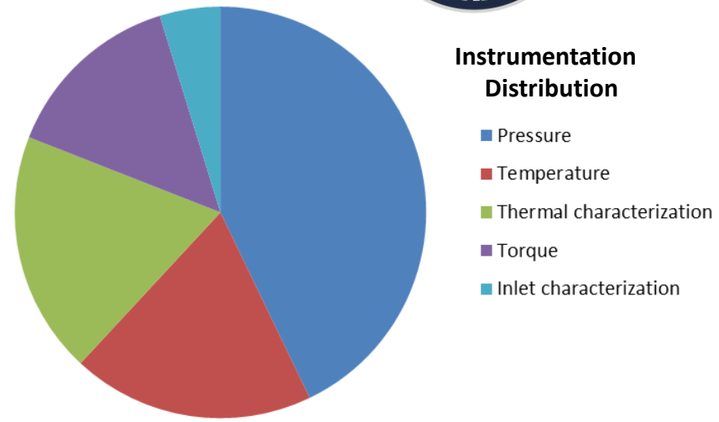
Analytical aero pre-test predictions completed, and are ready for experimental data comparison

Main gas path CFD has been coupled with secondary flow cavity CFD model for test correlation

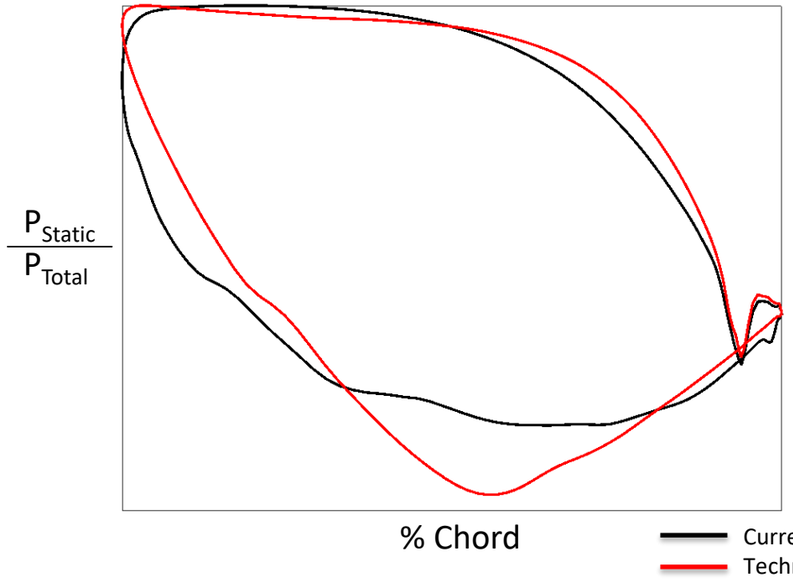
Additional instrumentation specific to technology blade testing completed

Primary effort in 2019 after completion of pre-test predictions was related to manufacturing of technology blades and implementation of test instrumentation

Initial tests in 2020 showed an instrumentation issue, followed by COVID shutdown, reactivation, and completion of the repeat aero testing



CFD Prediction for Pressure Distribution



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Penn State START Facility – Aero Preliminary Results

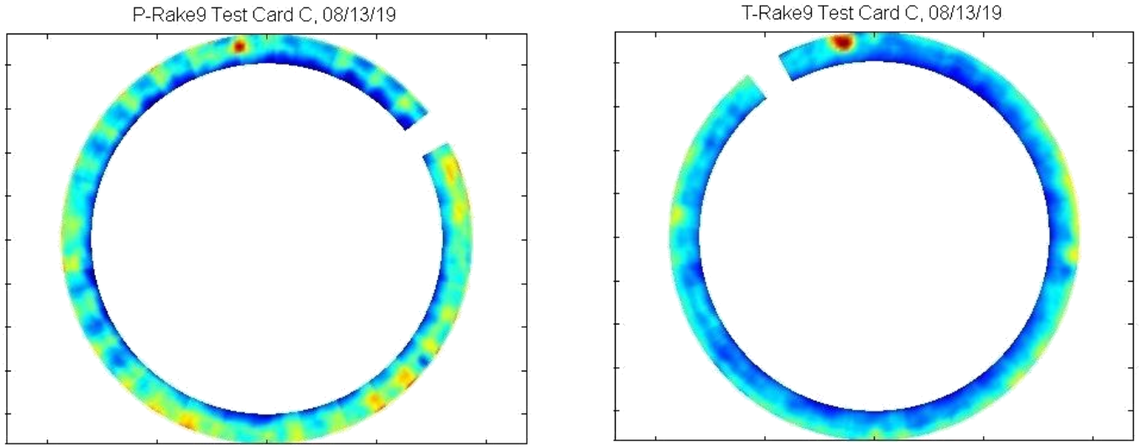
Data gathered and undergoing post-processing

Ensuring validity of the results and assessing repeatability of the test

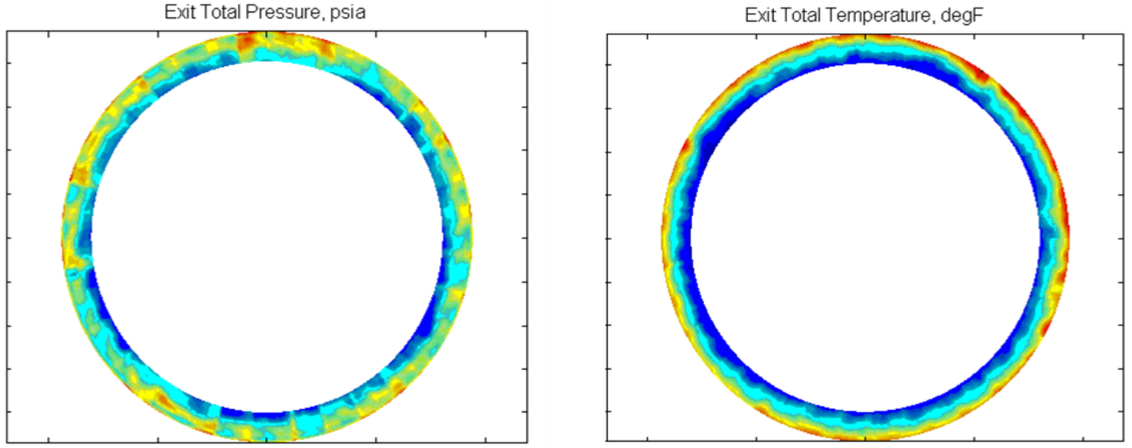
Data-matching prediction with measured data

Constructing Aero / CFD analysis with measured data for post-test conclusions

Baseline Blade Tests



Technology Blade Tests



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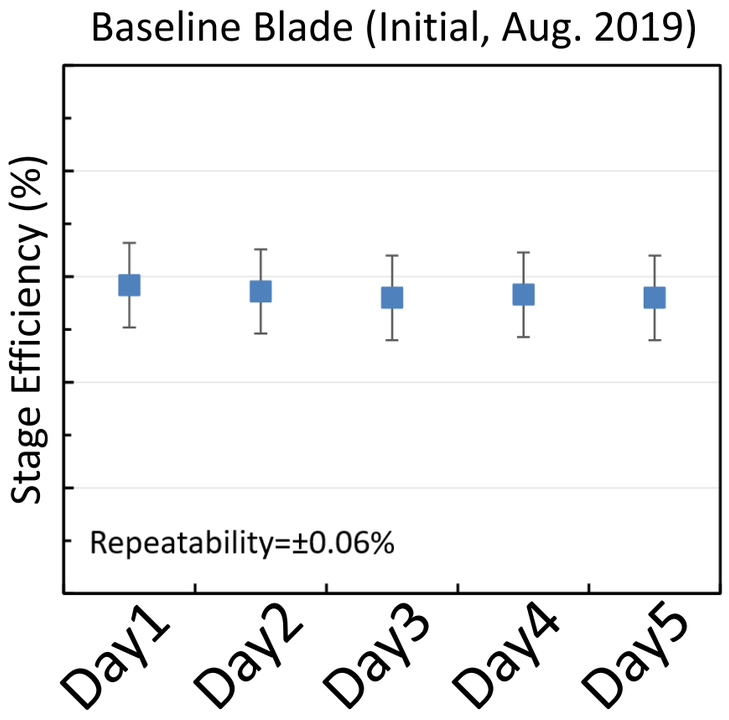
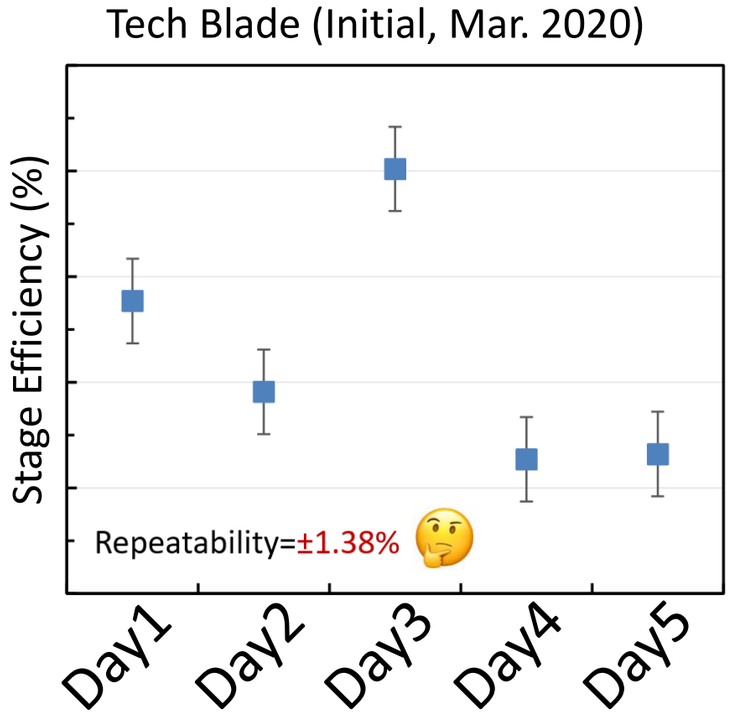
Penn State START Facility – Initial Testing Results

Tech blade data from March exhibited higher variability than expected.

Root cause investigation during COVID-19 shutdown traced to a failing power supply in a upstream pressure unit

Program was extended to allow repeat tests for both baseline and tech blades. This testing was completed in September 2020.





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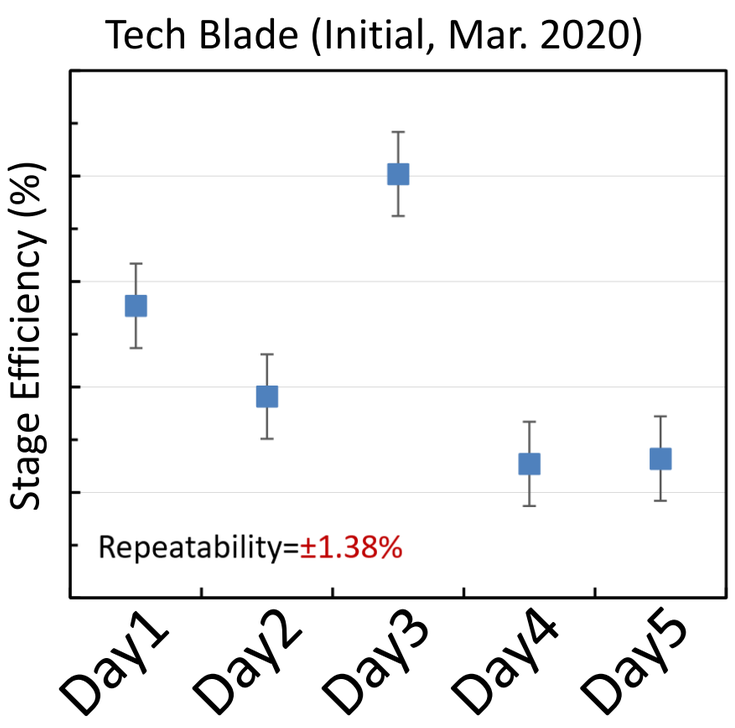
Penn State START Facility – Repeat Testing

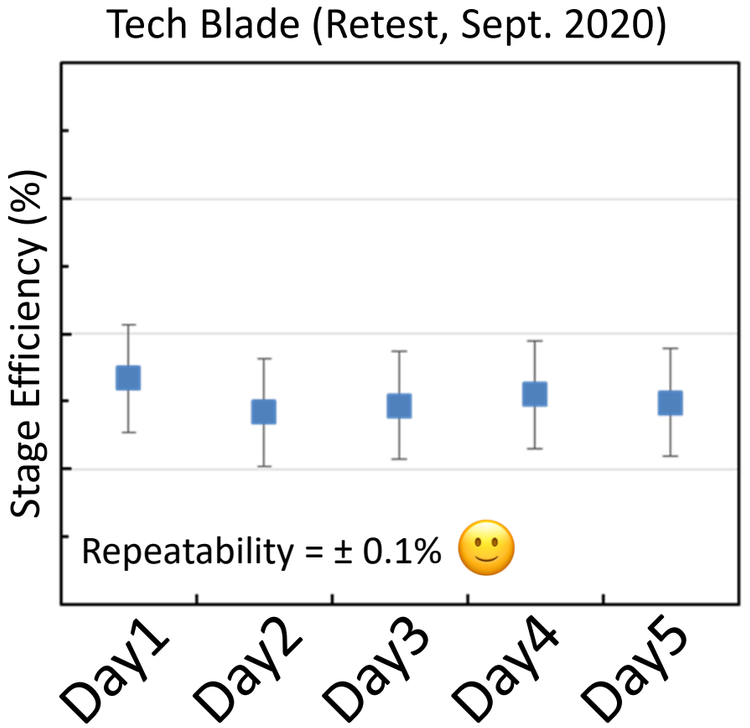
Repeat testing achieved its objective: more repeatable data

Tech blade repeat test was completed in August and baseline blade completed in September

Baseline blade retest is still under evaluation but early indications show repeatability also acceptable

Continued analysis and updating predictions for report writing





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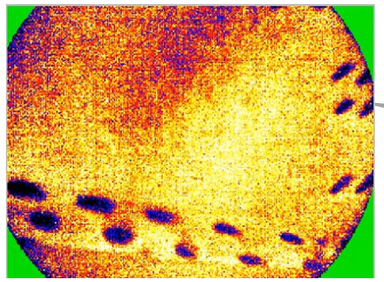
Penn State START Facility – Durability IR Mapping & Pre-test Predictions

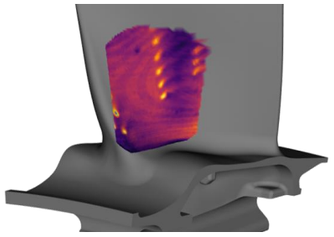
IR images gathering completed in Mar. 2020

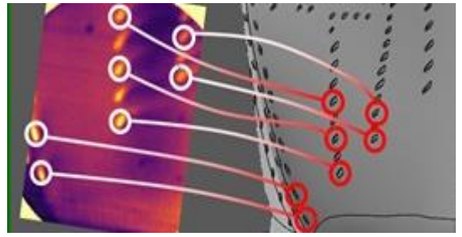
Mapping techniques developed and refined further since May – processing time reduced from hours to seconds

Currently updating internal flow models with as-manufactured flow test data and CT scan data



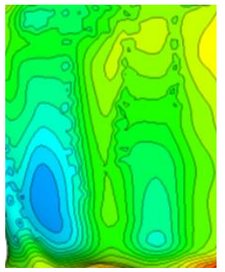
Raw Image Capture

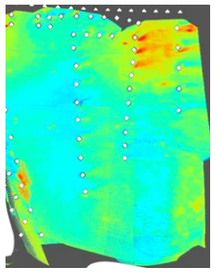




Mapping Process

Fully Processed & Mapped Blade Temperature Data





Note: Predicted and measured images do not represent same test conditions

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Penn State START Facility – Durability Preliminary Results

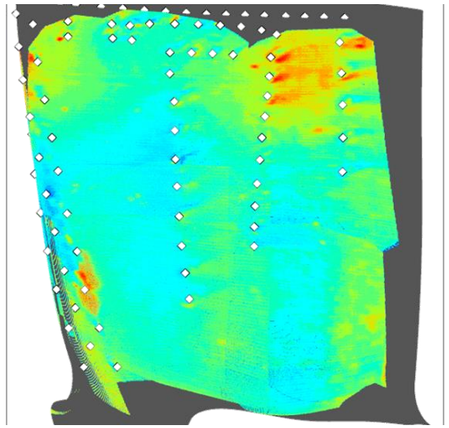
Final mapping of rig data to blade models completed.

Data normalization between the two rotor blade conditions ongoing in order to understand trends

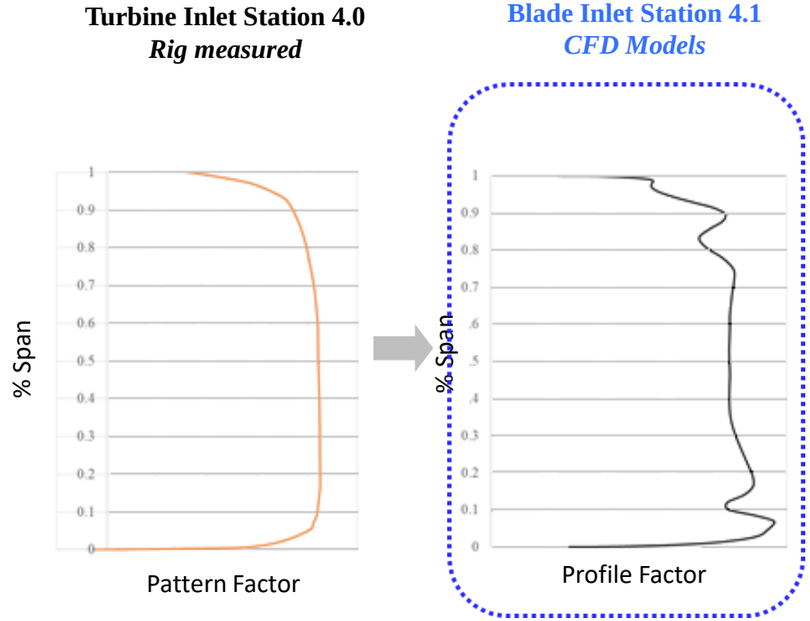
Rig measured results are being used to correlated Post-test CFD predictions

- CFD using rig measured boundary conditions has revealed the impact of upstream vane flow on blade boundary conditions.

- These findings currently being analyzed for data normalization & trends



Fully processed & mapped blade temperature data



L1 CFD boundary conditions updated to as-measured conditions for ST 4.1 predictions

Pratt & Whitney's CLEEN II Technologies

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PRATT & WHITNEY DEPENDABLE ENGINES

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Pratt & Whitney's CLEEN II Technologies

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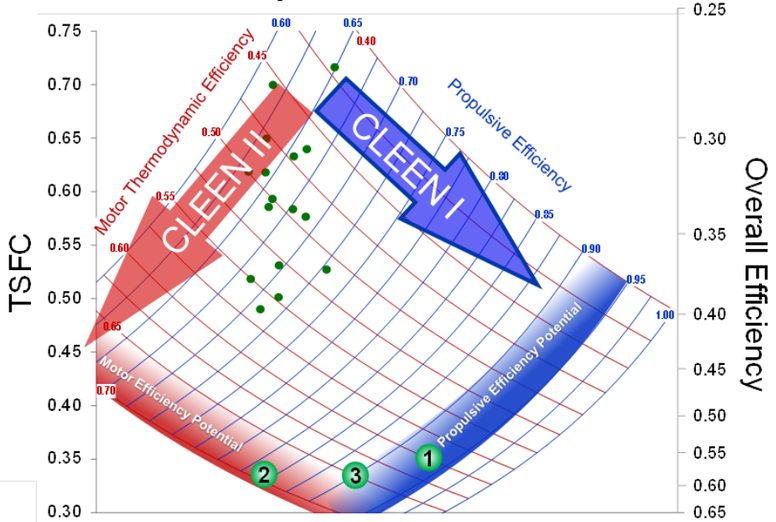
System Level Impact

CLEEN I increased the propulsive efficiency of the GTF engine with fan technologies

CLEEN II technologies continue to push towards more thermodynamically efficient turbofan engines.

Component Level



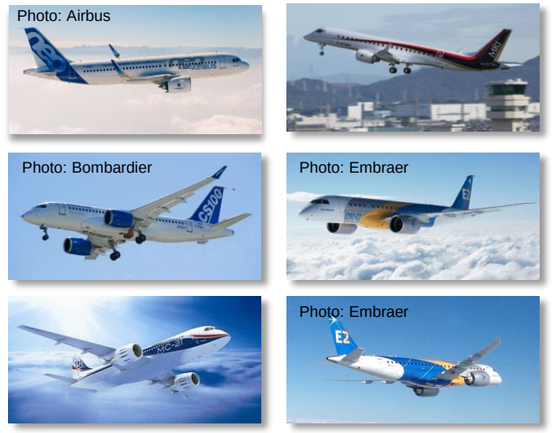
1 Whurr (RR)
2 Hall (MIT)
3 Carlson (GE)

Higher component efficiency

Engine / Airframe Level

1.6-2.0% Fuel Burn Reduction

Fleet Level



34-43K gallons of fuel savings per year per plane

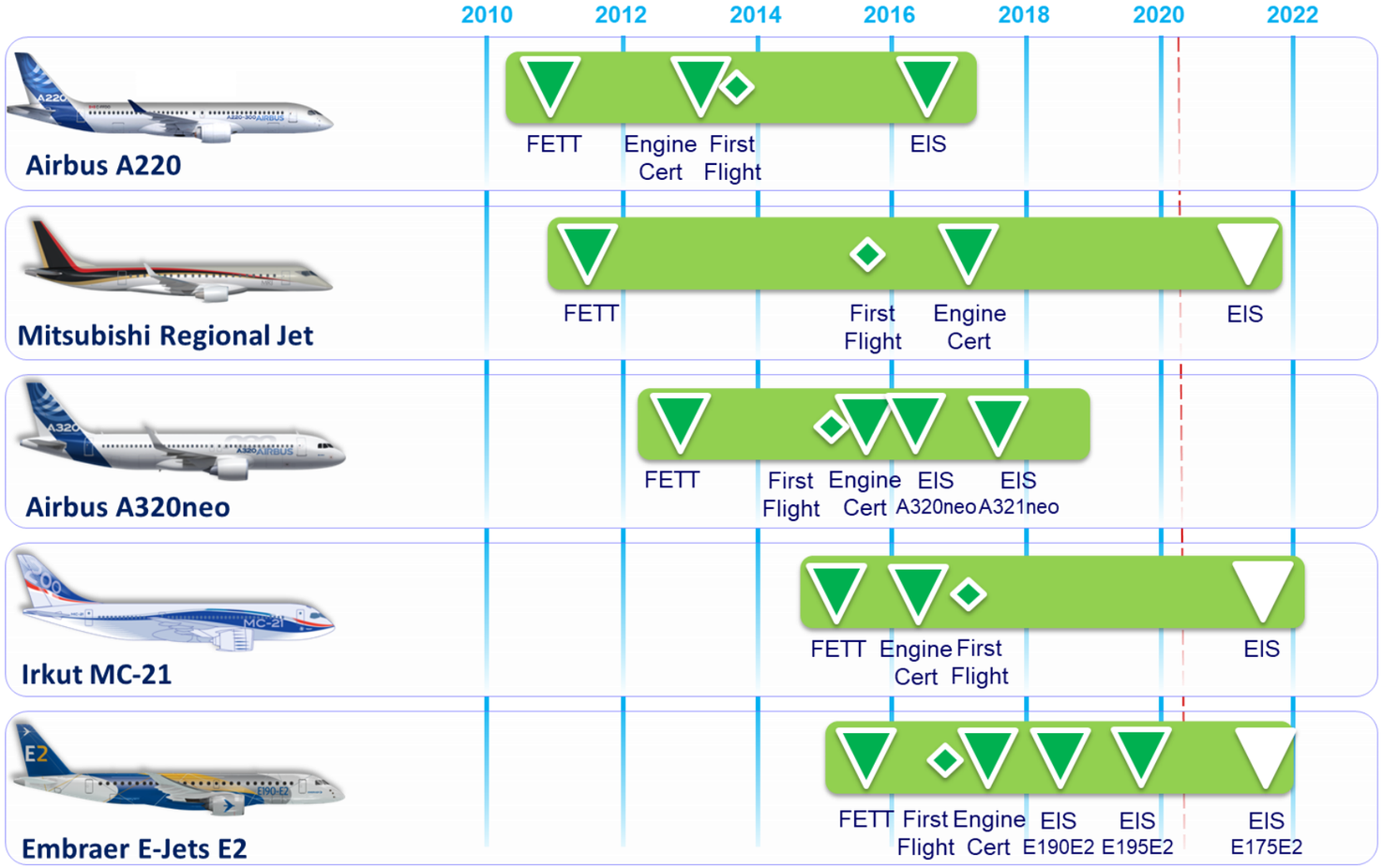
A320NEO, 2.0 hour flights, 3,100 annual flight hours

Pratt & Whitney's CLEEN II Technologies

GO BEYOND

80+ Customers/10,000+ Engine Orders and Commitments

738 a/c in service (605 neo, 113 A220, 20 E2)
Total of 5.5M Engine Flight Hours and 3M Engine Flight Cycles
260M gallons of fuel saved, 2.6M tons CO2 reduced relative to current engine offerings



Pratt & Whitney's CLEEN II Technologies

GO BEYOND

Program Summary

High Pressure Compressor (HPC)

- ✓ Product-like HPC rig overachieved efficiency goal
- ✓ HPC tested in ground and flight test engines to achieved TRL-7
- ✓ Active campaign for product insertion ongoing

High Pressure Turbine (HPT)

- ✓ FAA assisted in the enhancement of PSU's world-class START facility
- ✓ Successfully tested novel technologies using new methods in representative environment
- ✓ Achieved TRL-5 for durability technologies; TRL-6 for aerodynamic technologies

Highly Successful Program

- ✓ Successful completion of program milestones in the face of COVID and technical challenges
- ✓ Completion of program on-budget

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